RF Fundamentals Seminar
Part 6: Vector Signal Analysis and Intro to OFDM

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Make ideas real

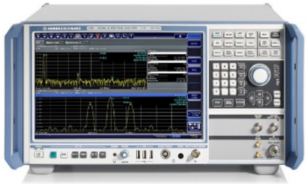
Today's Presenter

- Greg Vaught
- Rohde & Schwarz application engineer for 14 years
- Based in Illinois, covering the territory of the central part of the US
- Supports Signal Generators, Spectrum Analyzers, Vector Network Analyzers, and Power Meters
- Email: gregory.vaught@rsa.rohde-schwarz.com

Agenda – RF Fundamentals Part 6

- **Vector Signal Analysis**
- Vector Signal Analysis Demonstration
- Introduction to OFDM

Measuring Digitally Modulated Signals



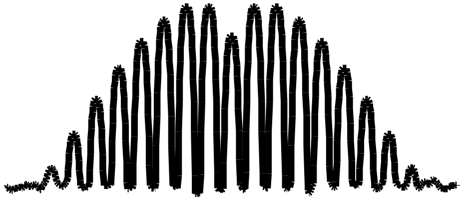
- Can I use a basic Spectrum Analyzer to measure modulation quality?
- No. A spectrum analyzer can measure power, occupied bandwidth, and spectral purity, but to measure modulation quality you need a Vector Signal Analyzer (VSA)

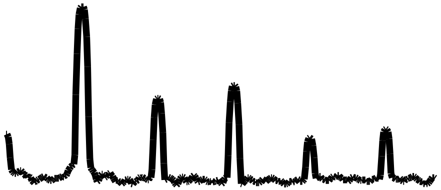
- Is a VSA a completely separate instrument?
- No. It's usually an option to a spectrum analyzer
  - It uses an IQ digitizer and demodulator which are not generally used in spectrum analysis
  - It adds software with sophisticated algorithms to synchronize to the signal and measure it

- What are the key parameters to consider in a VSA?
- Bandwidth (maximum symbol rate) and Inherent Modulation Quality of the instrument. These two characteristics typically divide VSA into classes: High-end, mid-range, etc.

Modulation Quality Measurements

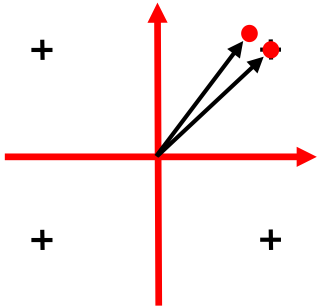
Analog Modulation

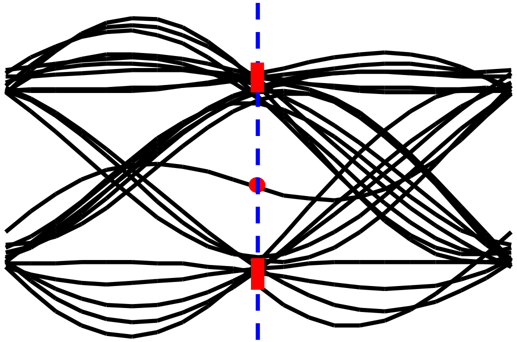




FM Deviation, AM Depth, Audio Distortion, etc.

Digital Modulation

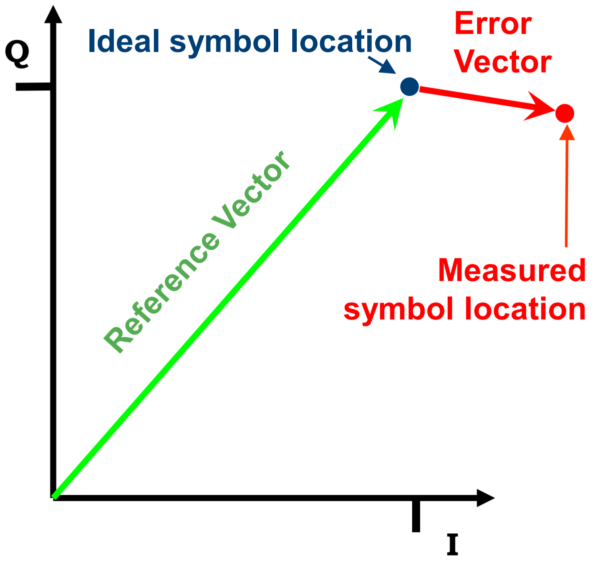




EVM, rho, I-Q offset (carrier feedthrough), etc.

What is EVM?

- EVM is the single most measured quantity on digitally modulated signals
- The ‘reference vector’ represents the ideal symbol location in the IQ plane
- The error vector is the vector between the ideal symbol location and the measured symbol location
- EVM is the ratio of the error vector to the reference vector
- EVM is this ratio expressed as % or dB
  - EVM (%) = | error / ref | x 100
  - EVM (dB) = 20 log (| error / ref |)



What is EVM?

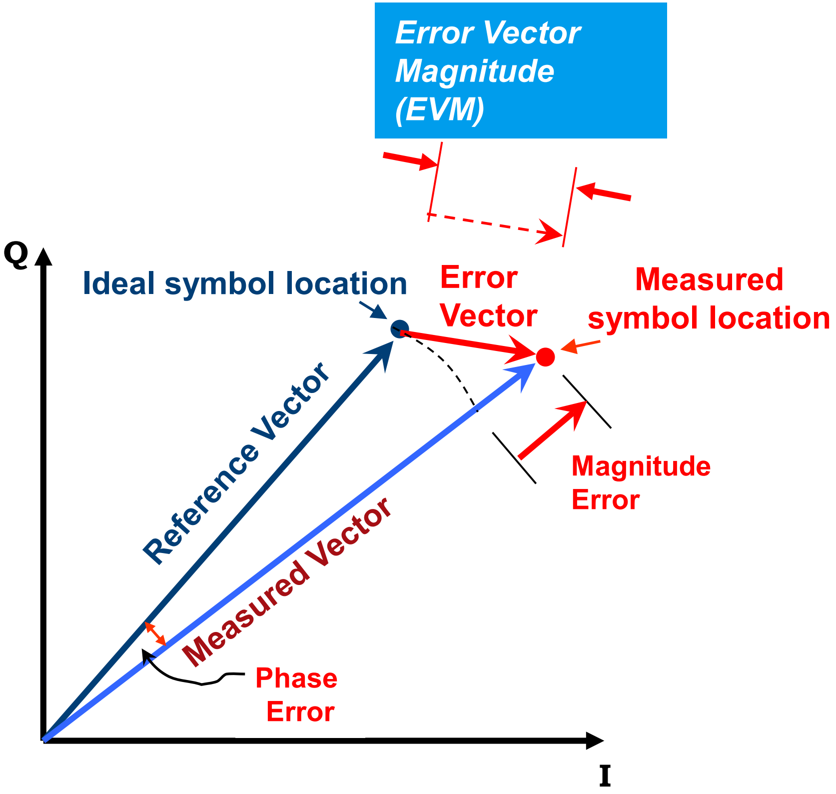
- EVM can be broken down into its components of Magnitude Error and Phase Error
- The relative contribution of these components can aid in troubleshooting EVM issues

1 Result Summary

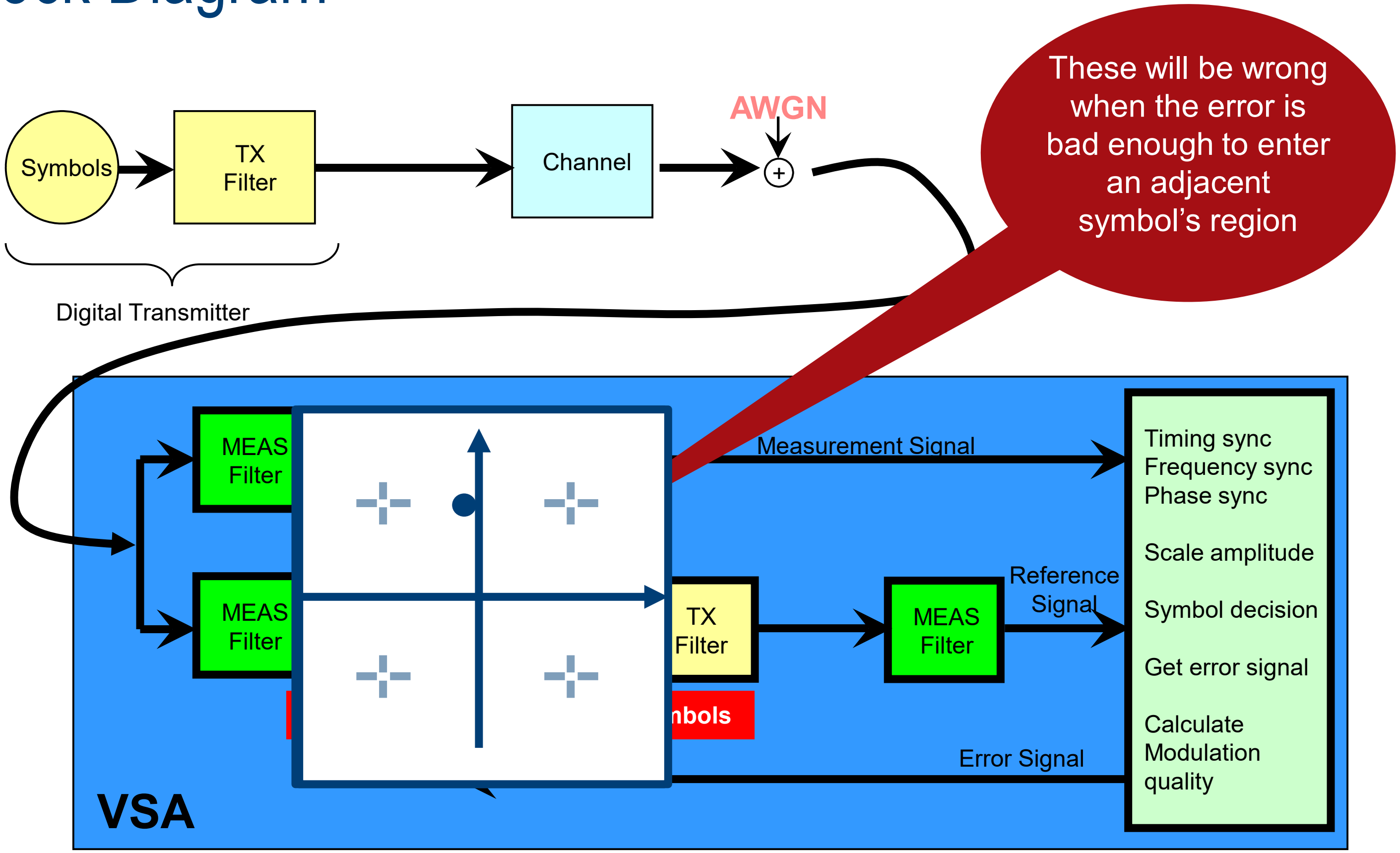
		Current	Peak	Unit
EVM	RMS	**0.19**	0.22	%
	Peak	**0.43**	0.56	%
MER	RMS	**54.65**	53.34	dB
	Peak	**47.36**	45.05	dB
Phase Error	RMS	**0.08**	0.09	deg
	Peak	**-0.23**	0.32	deg
Magnitude Error	RMS	**0.13**	0.16	%
	Peak	**0.36**	0.52	%

MER (Modulation Error Ratio) is EVM expressed in dB

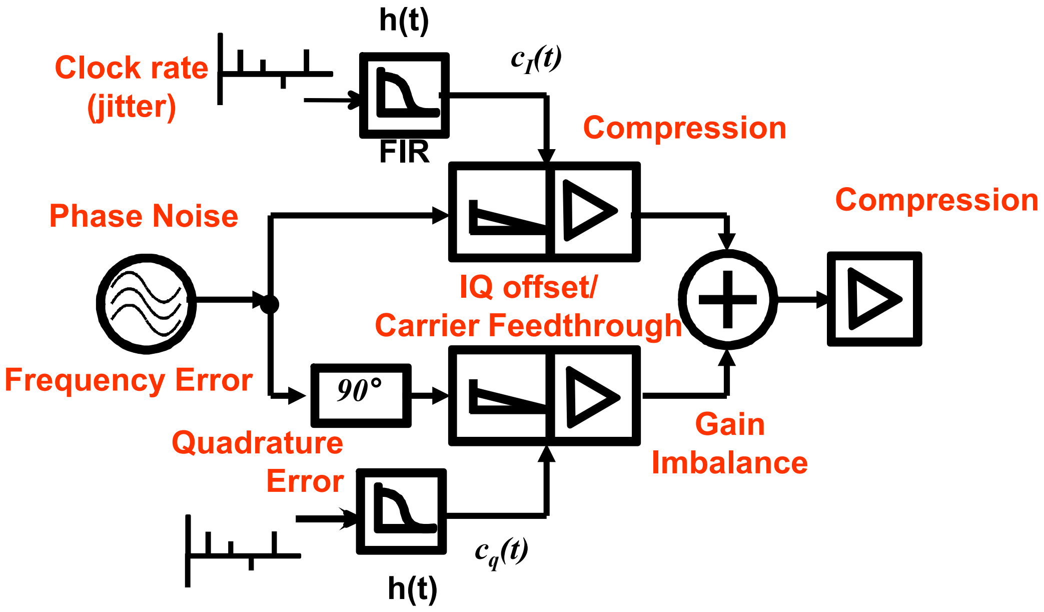
- Example: EVM = 1% = -40 dB → MER = 40 dB



VSA: Block Diagram

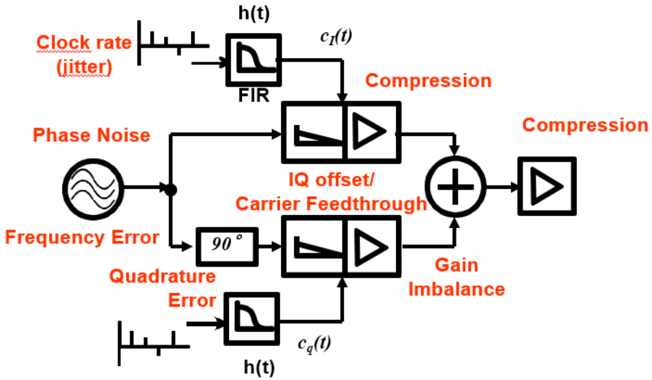


Sources of Modulation Error



In-Band Spurious

- Spurious CW signal within the channel bandwidth will cause the constellation points to have a ‘donut’ shape
- Easy to identify in constellation diagram
- Typical source is switching power supply clock or other oscillator in the DUT leaking into the IQ modulator



2 Result Summary

		Current	Peak	Unit
EVM	RMS	9.95	10.02	%
	Peak	12.06	13.02	%
MER	RMS	20.05	19.98	dB
	Peak	18.37	17.71	dB
Phase Error	RMS	4.02	4.08	deg
	Peak	6.46	-6.80	deg
Magnitude Error	RMS	7.07	7.15	%
	Peak	-11.40	-12.29	%
Carrier Frequency Error		-4.96	-8.40	Hz
Symbol Rate Error		-9.67	-28.61	ppm
I/Q Skew		---	---	ps
Rho		0.990 125	0.990 046	
I/Q Offset		-50.13	-49.37	dB
I/Q Imbalance		-54.68	-54.20	dB
Gain Imbalance		0.03	0.03	dB
Quadrature Error		0.07	0.22	deg
Amplitude Droop		-0.000 10	0.000 084	dB/sym
Power		0.86	0.91	dBm

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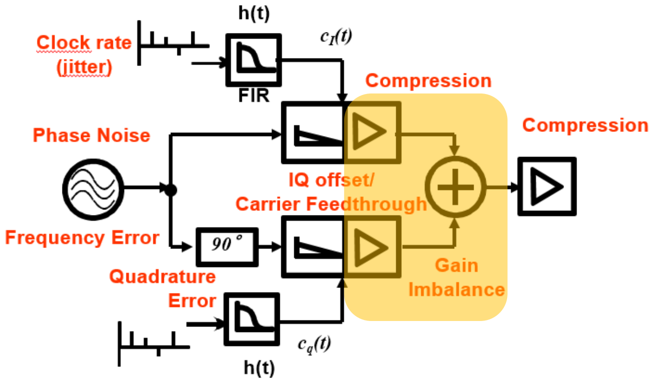
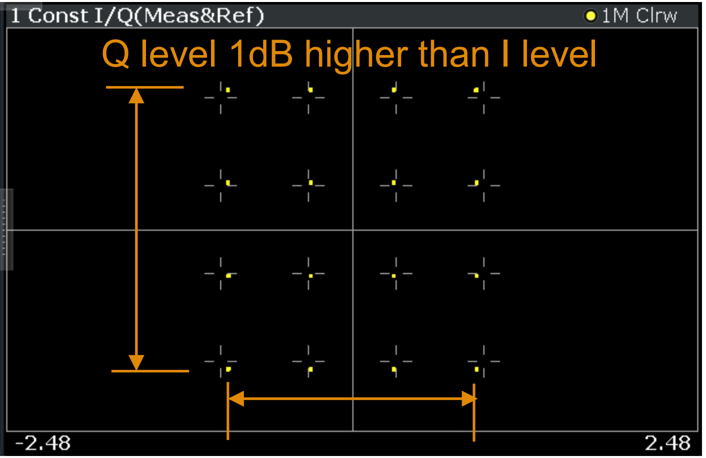
IQ Gain (or Amplitude) Imbalance



► Caused by unequal gain between I and Q paths

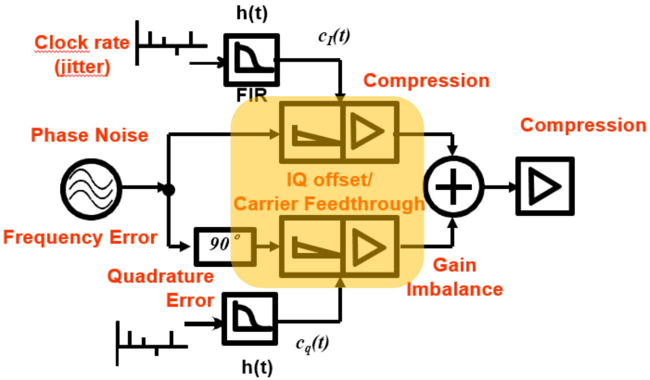
2 Result Summary

		Current	Peak	Unit
EVM	RMS	5.73	5.73	%
	Peak	7.97	8.04	%
MER	RMS	24.84	24.84	dB
	Peak	21.97	21.89	dB
Phase Error	RMS	2.71	2.72	deg
	Peak	-3.88	-3.90	deg
Magnitude Error	RMS	3.22	3.29	%
	Peak	5.05	5.07	%
Carrier Frequency Error		-3.04	-3.06	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.996 734	0.996 729	
I/Q Offset		-60.78	-60.70	dB
I/Q Imbalance		-24.85	-24.84	dB
Gain Imbalance		1.00	1.00	dB
Quadrature Error		0.06	0.06	deg
Amplitude Droop		0.000 000	0.000 001	dB/sym
Power		0.14	0.18	dBm



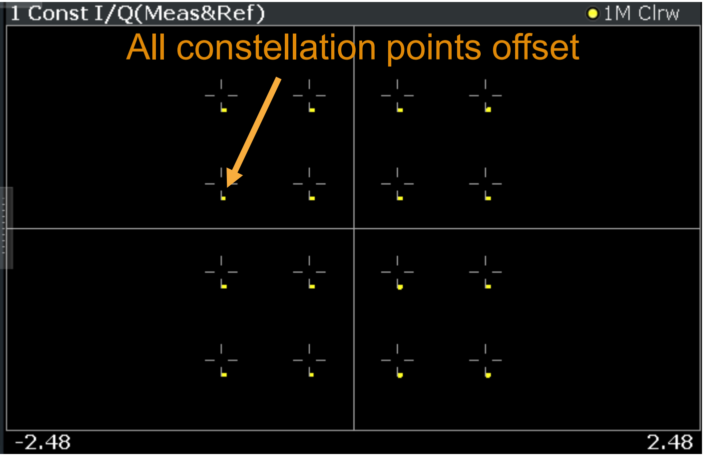
IQ Offset (Carrier Feedthrough)

- IQ Offset results in the whole constellation being offset in the I and/or Q direction
- IQ Offset is caused by small DC levels at the I/Q modulator
- Low levels of offset are not visually obvious, but are measured down to very low levels in the Result Summary



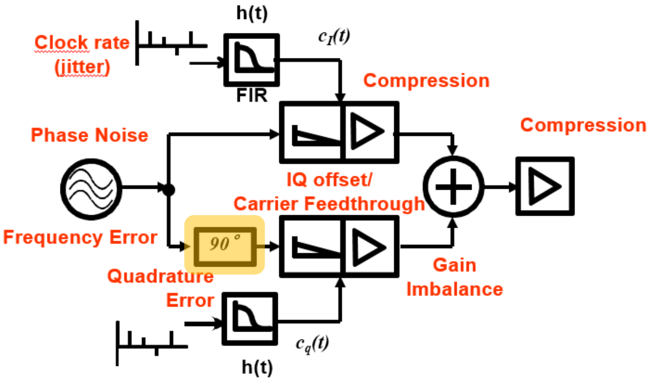
2 Result Summary

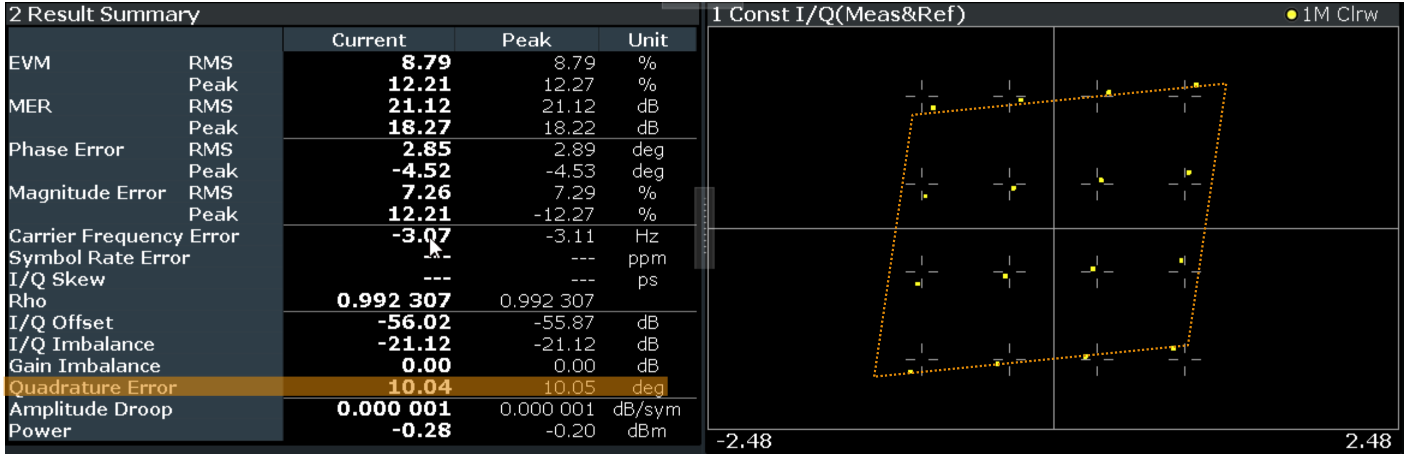
		Current	Peak	Unit
EVM	RMS	10.58	10.66	%
	Peak	11.02	11.10	%
MER	RMS	19.51	19.44	dB
	Peak	19.16	19.10	dB
Phase Error	RMS	6.02	6.04	deg
	Peak	-13.19	-13.24	deg
Magnitude Error	RMS	7.41	7.57	%
	Peak	10.87	10.93	%
Carrier Frequency Error		-3.03	-3.07	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.988 943	0.988 742	
I/Q Offset		-19.51	-19.44	dB
I/Q Imbalance		-67.66	-66.36	dB
Gain Imbalance		0.00	0.01	dB
Quadrature Error		0.04	0.04	deg
Amplitude Droop		0.000 001	0.000 001	dB/sym
Power		-0.19	-0.14	dBm



Quadrature Error

- ► Quadrature error results when the angle between I and Q is not 90 degrees
- ► This impairment changes the constellation from a square to a parallelogram
- ► Quadrature error is most easily seen in the Result Summary





2 Result Summary

		Current	Peak	Unit
EVM	RMS	8.79	8.79	%
	Peak	12.21	12.27	%
MER	RMS	21.12	21.12	dB
	Peak	18.27	18.22	dB
Phase Error	RMS	2.85	2.89	deg
	Peak	-4.52	-4.53	deg
Magnitude Error	RMS	7.26	7.29	%
	Peak	12.21	-12.27	%
Carrier Frequency Error		-3.07	-3.11	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.992 307	0.992 307	
I/Q Offset		-56.02	-55.87	dB
I/Q Imbalance		-21.12	-21.12	dB
Gain Imbalance		0.00	0.00	dB
Quadrature Error		10.04	10.05	deg
Amplitude Droop		0.000 001	0.000 001	dB/sym
Power		-0.28	-0.20	dBm

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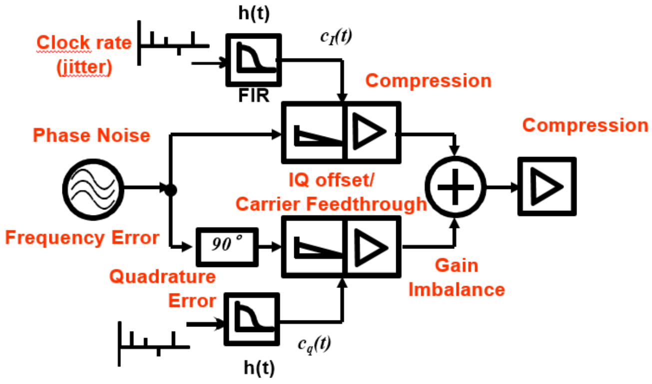
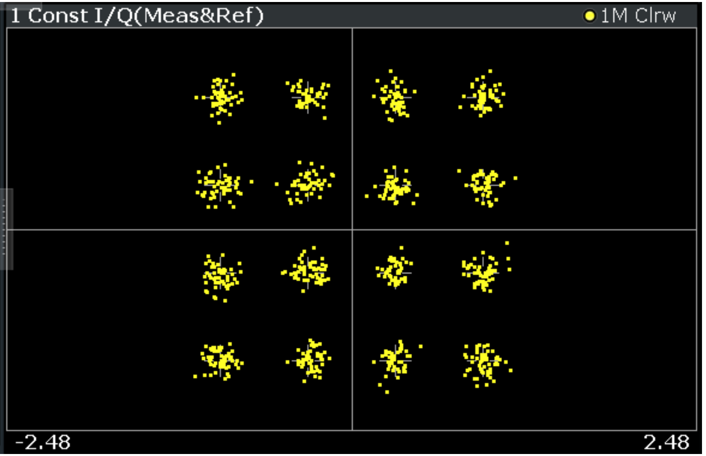
Low Signal to Noise Ratio
SNR: 20 dB

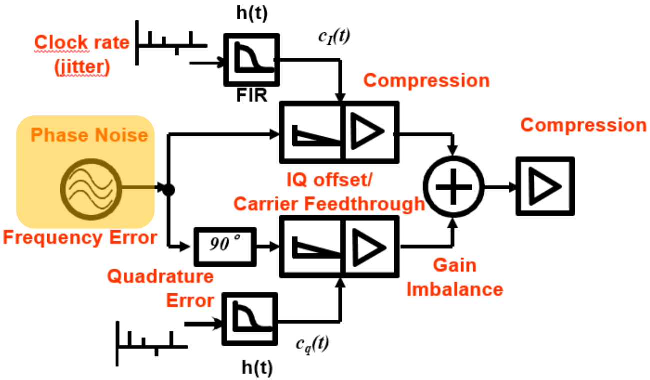


2 Result Summary

		Current	Peak	Unit
EVM	RMS	9.77	10.22	%
	Peak	27.97	35.46	%
MER	RMS	20.20	19.81	dB
	Peak	11.07	9.01	dB
Phase Error	RMS	5.72	5.88	deg
	Peak	-25.78	-34.49	deg
Magnitude Error	RMS	6.85	7.33	%
	Peak	23.76	-34.60	%
Carrier Frequency Error		-1.37	-5.04	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.990 527	0.989 678	
I/Q Offset		-47.52	-39.96	dB
I/Q Imbalance		-65.46	-42.31	dB
Gain Imbalance		0.01	0.05	dB
Quadrature Error		0.00	0.88	deg
Amplitude Droop		-0.000 01	0.000 109	dB/sym
Power		-0.01	0.03	dBm



Phase Noise

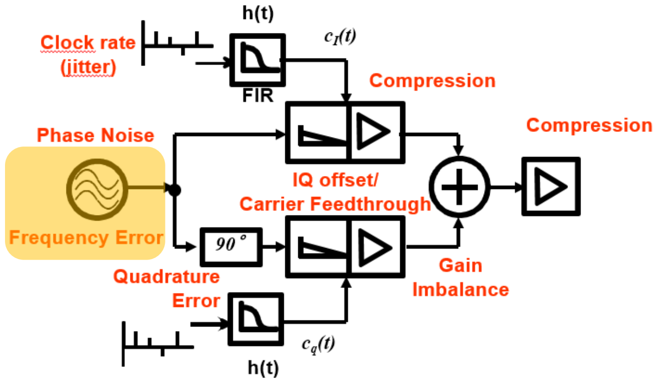


- ► Phase noise forms arcs of noise at the symbol points
- ► Caused by high phase noise in LO/carrier
- ► Also indicated by high Phase Error value (relative to Mag Error)

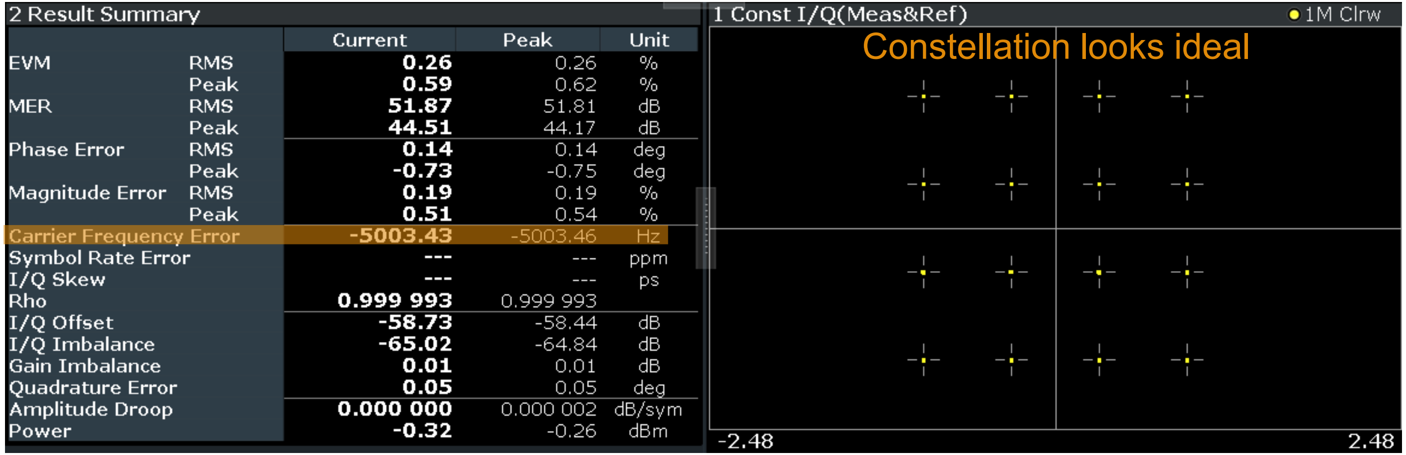
2 Result Summary

		Current	Peak	Unit
EVM	RMS	4.14	4.69	%
	Peak	17.70	19.64	%
MER	RMS	27.66	26.58	dB
	Peak	15.04	14.14	dB
Phase Error	RMS	2.33	2.68	deg
	Peak	-8.07	-8.60	deg
Magnitude Error	RMS	0.45	0.46	%
	Peak	1.57	2.44	%
Carrier Frequency Error		-1.61	-5.71	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.998 292	0.997 806	
I/Q Offset		-58.01	-50.05	dB
I/Q Imbalance		-56.87	-50.57	dB
Gain Imbalance		0.01	0.04	dB
Quadrature Error		0.16	0.23	deg
Amplitude Droop		0.000 007	0.000 007	dB/sym
Power		-0.18	-0.06	dBm

Carrier Frequency Error



- Carrier frequency error is simply the difference between the actual and the intended output center frequency
- Caused by error in the DUT's frequency reference
- Frequency error is not visible in the constellation and must be read in the Result Summary

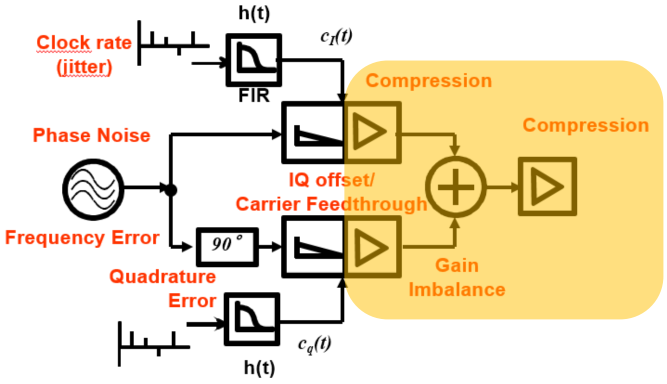


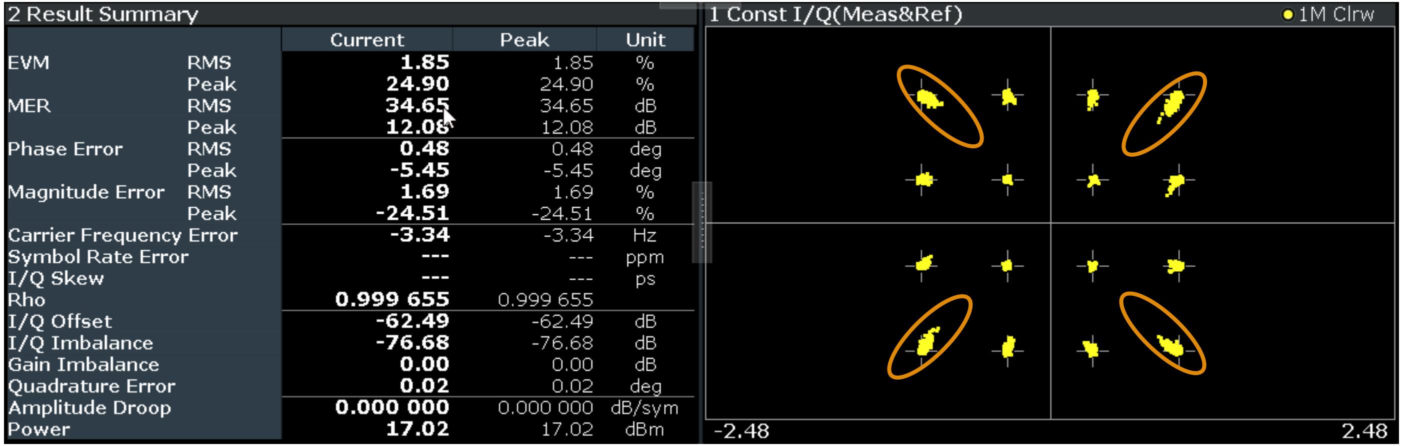
2 Result Summary

		Current	Peak	Unit
EVM	RMS	0.26	0.26	%
	Peak	0.59	0.62	%
MER	RMS	51.87	51.81	dB
	Peak	44.51	44.17	dB
Phase Error	RMS	0.14	0.14	deg
	Peak	-0.73	-0.75	deg
Magnitude Error	RMS	0.19	0.19	%
	Peak	0.51	0.54	%
Carrier Frequency Error		-5003.43	-5003.46	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.999 993	0.999 993	
I/Q Offset		-58.73	-58.44	dB
I/Q Imbalance		-65.02	-64.84	dB
Gain Imbalance		0.01	0.01	dB
Quadrature Error		0.05	0.05	deg
Amplitude Droop		0.000 000	0.000 002	dB/sym
Power		-0.32	-0.26	dBm

Compression

- ► Compression has a subtle effect in the constellation – the outermost symbols (those with the highest power level) are smeared toward the origin
- ► Compression can result from overdriving the IQ modulator or output amplifier



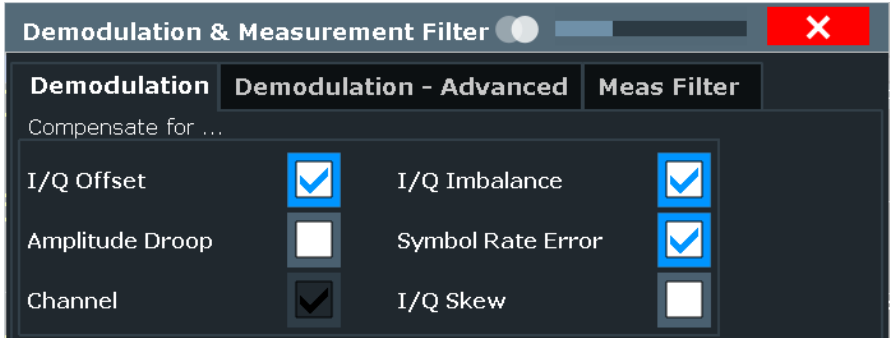


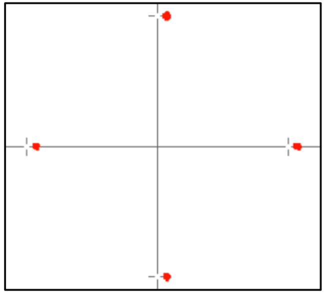
2 Result Summary

		Current	Peak	Unit
EVM	RMS	1.85	1.85	%
	Peak	24.90	24.90	%
MER	RMS	34.65	34.65	dB
	Peak	12.08	12.08	dB
Phase Error	RMS	0.48	0.48	deg
	Peak	-5.45	-5.45	deg
Magnitude Error	RMS	1.69	1.69	%
	Peak	-24.51	-24.51	%
Carrier Frequency Error		-3.34	-3.34	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.999 655	0.999 655	
I/Q Offset		-62.49	-62.49	dB
I/Q Imbalance		-76.68	-76.68	dB
Gain Imbalance		0.00	0.00	dB
Quadrature Error		0.02	0.02	deg
Amplitude Droop		0.000 000	0.000 000	dB/sym
Power		17.02	17.02	dBm

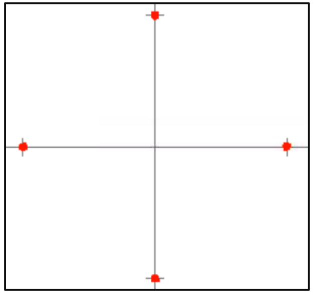
The VSA Can Compensate Some of these Errors

- ► Why do this, isn't it cheating?
- ► If you expect your receiver will do this, then it makes sense to also compensate it with the VSA
- ► Note these are systematic, predictable errors





Not Compensated



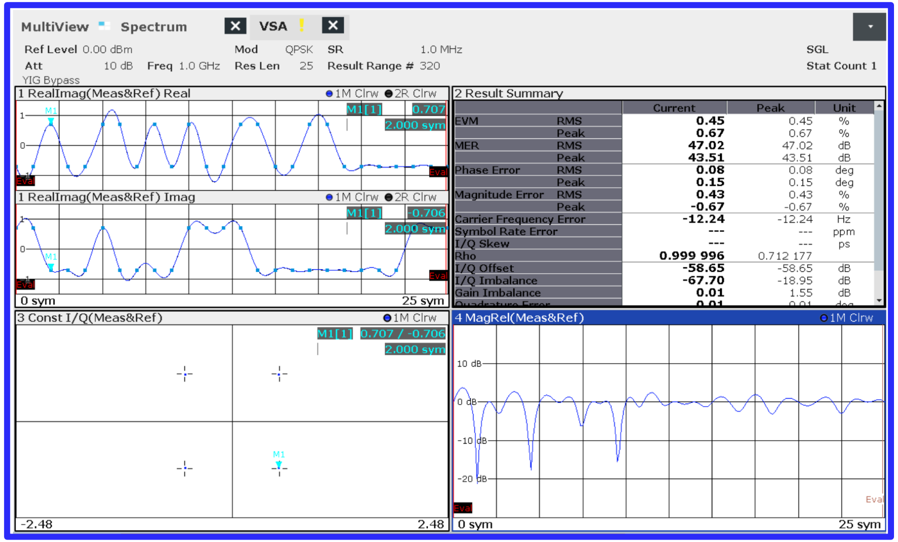
Compensated

Example: IQ Offset of 2.5%

Agenda – RF Fundamentals Part 6

- ► Vector Signal Analysis
- ► **Vector Signal Analysis Demonstration**
- ► Introduction to OFDM

Vector Signal Analysis

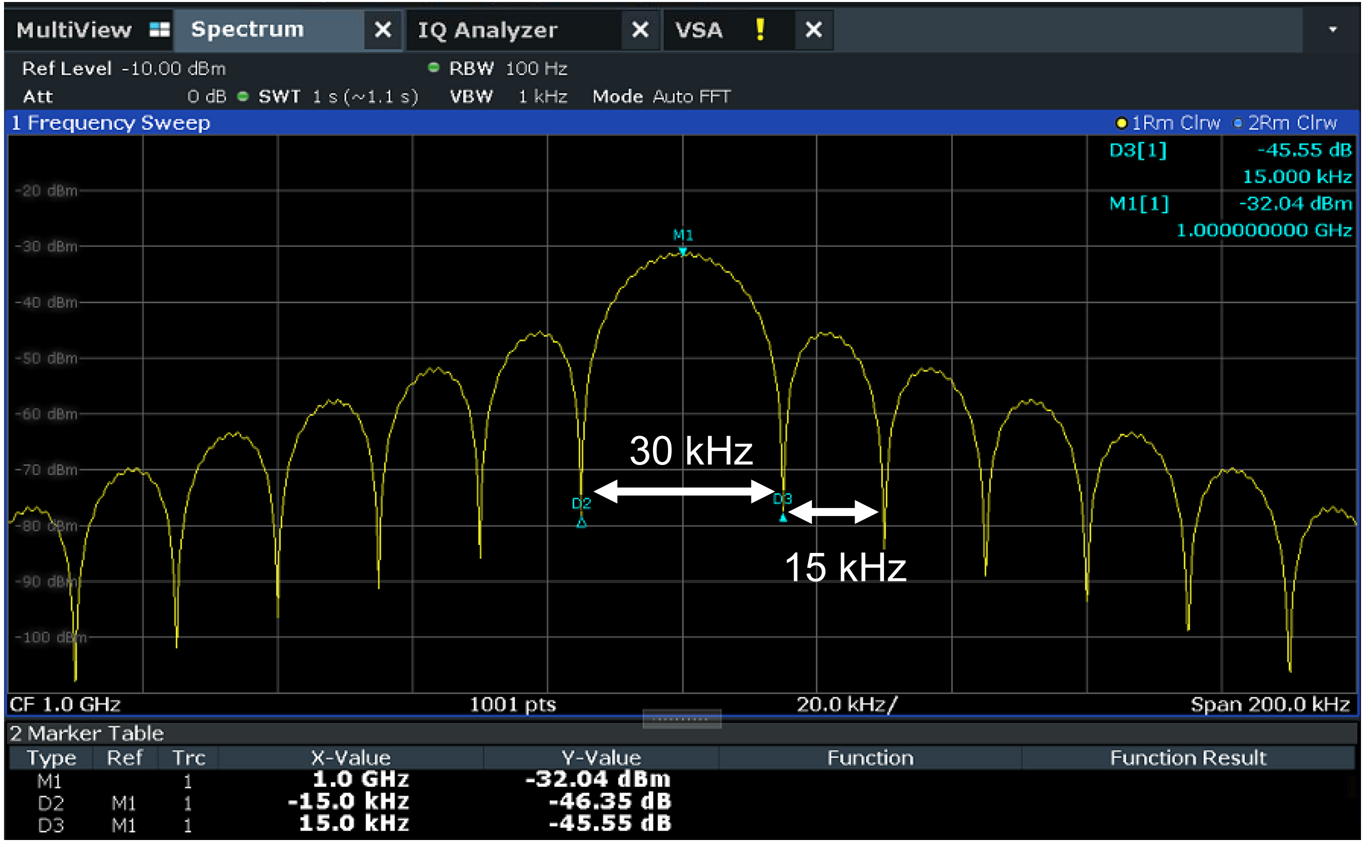


Demo Time!

Agenda – RF Fundamentals Part 6

- ► Vector Signal Analysis
- ► Vector Signal Analysis Demonstration
- ► **Introduction to OFDM**

Remember the Rectangular Filter?

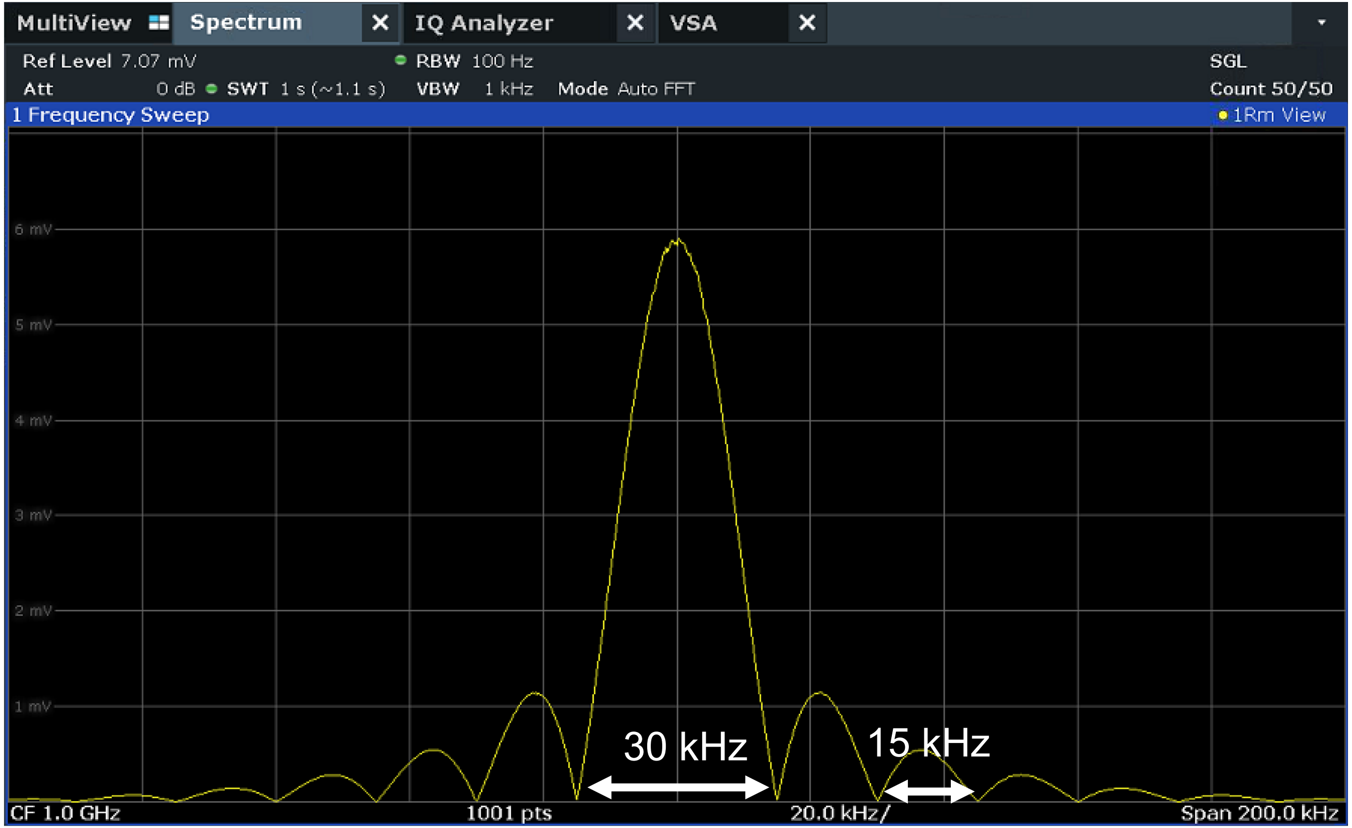


Signal Properties:

QPSK Modulation
Rectangular Filter
Symbol rate 15 ksps

sin (x) / x shape

Two Carriers Spaced by the Symbol Rate Frequency

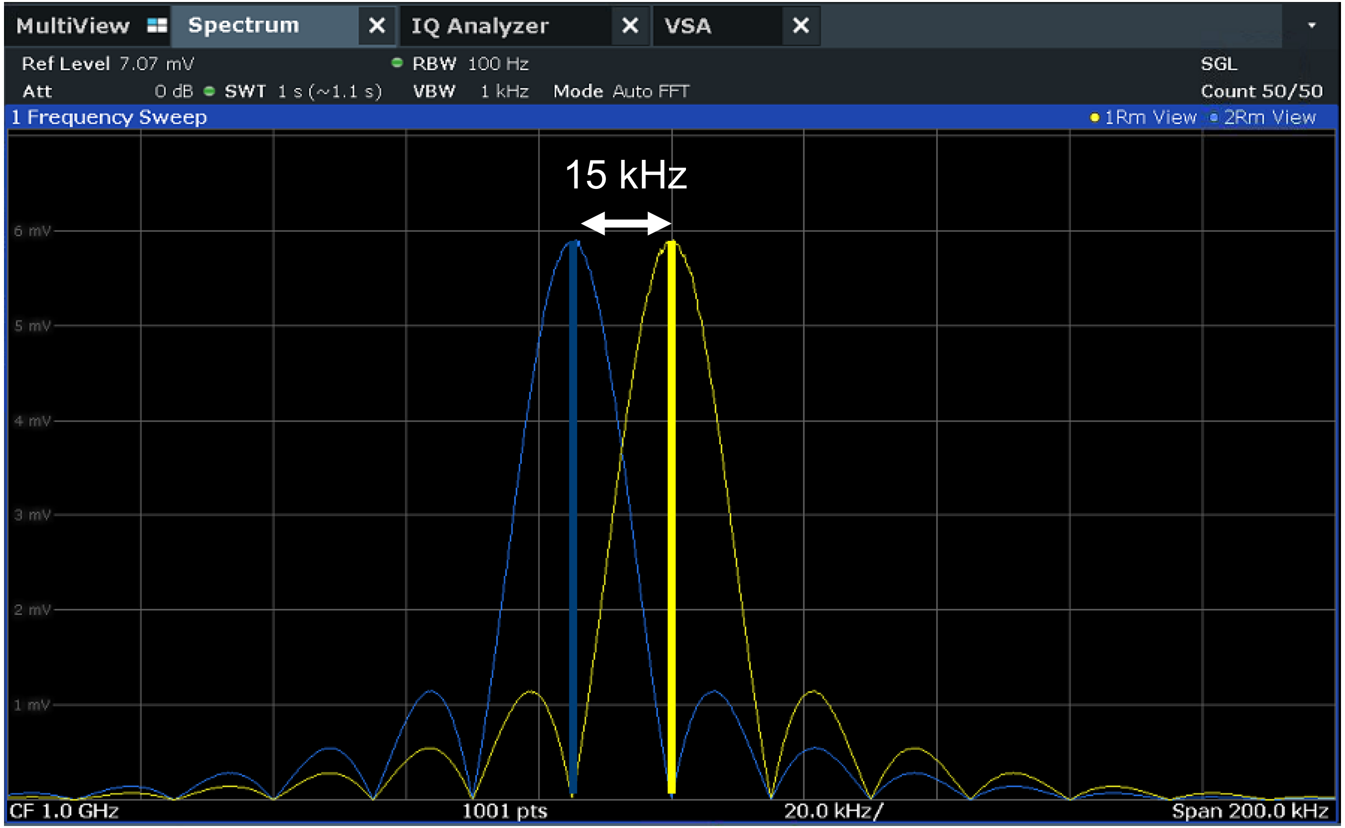


Signal Properties:

QPSK Modulation
Rectangular Filter
Symbol rate 15 ksps

Switched to a linear scale

Two Carriers Spaced by the Symbol Rate Frequency



Signal Properties:

QPSK Modulation
Rectangular Filter
Symbol rate 15 ksps

Five Carriers Spaced by the Symbol Rate Frequency

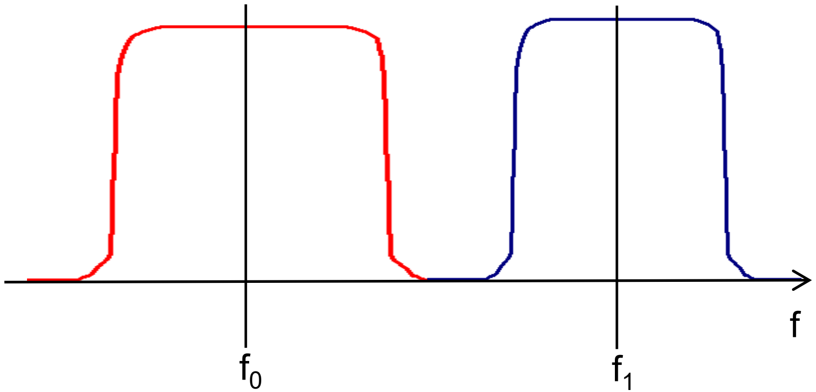
Signal Properties:

QPSK Modulation
Rectangular Filter
Symbol rate 15 ksps

This is the basis of Orthogonal carriers

OFDM: What is Orthogonal?

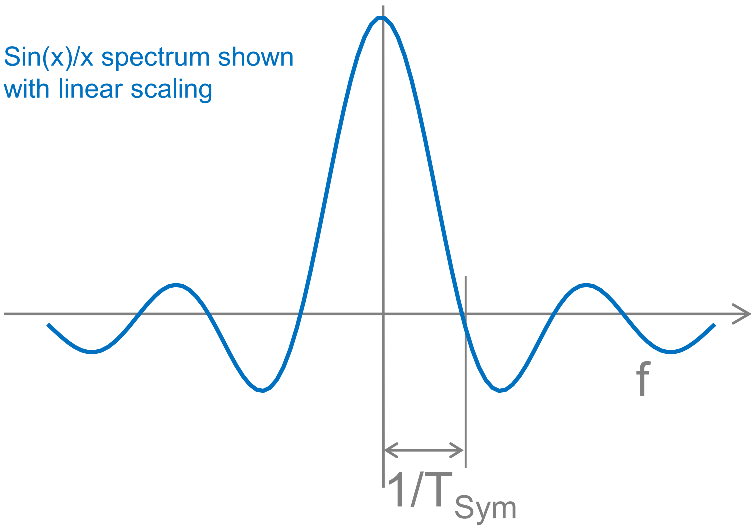
- FDM: Frequency Division Multiplexing
- Conventional FDM System: Space carriers sufficiently to avoid interference

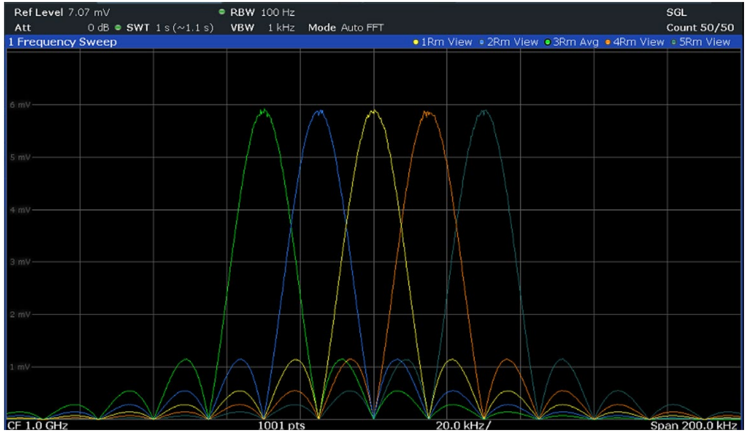


FDM

OFDM: What is Orthogonal?

- Orthogonal Frequency Division Multiplexing
- Use properties of sin(x)/x characteristic

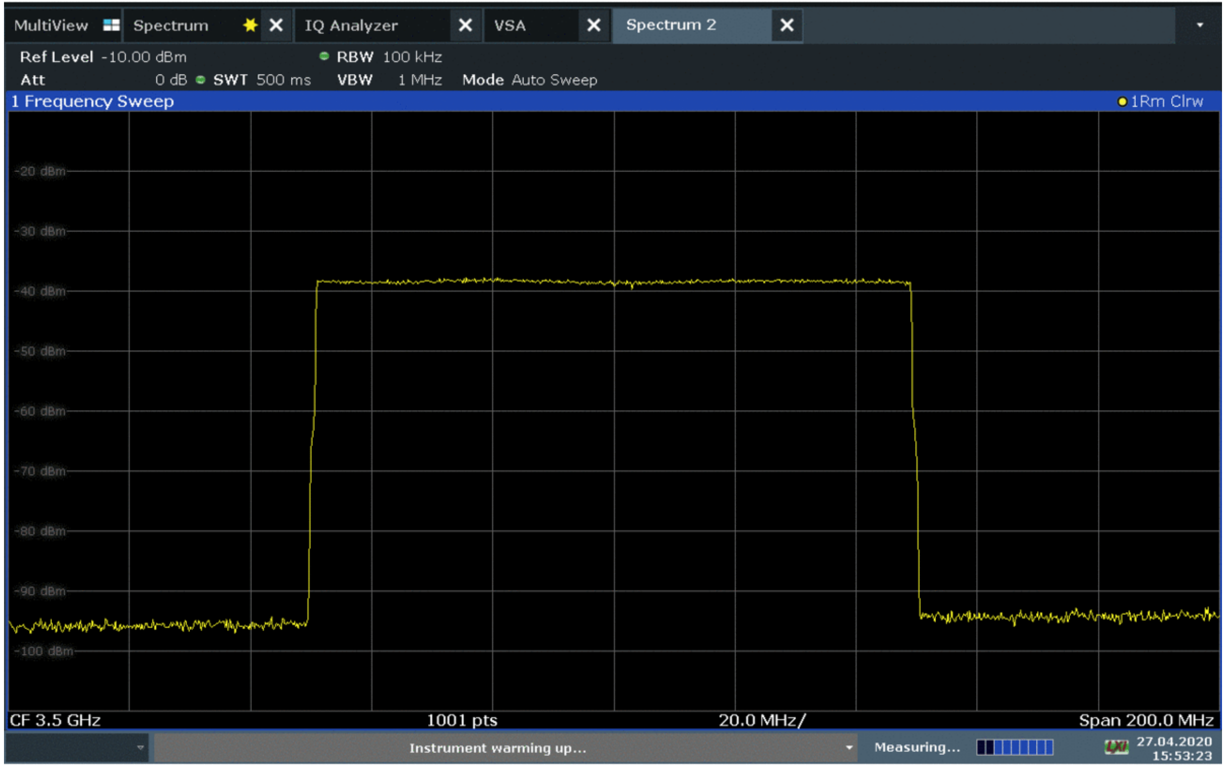




Where is OFDM Used?

- Cellular:
  - LTE (4G)
  - 5G New Radio
- WiFi Standards (IEEE 802.11)
- Terrestrial Radio
  - HD Radio
  - DAB (Digital Audio Broadcasting)
- Terrestrial Television
  - DVB-T (Digital Video Broadcasting – Terrestrial)
  - ATSC 3.0 (Advanced Television Standards Committee)
- DOCSIS 3.1 (Latest generation Cable Standard)

Example: 100 MHz 5G NR Signal



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5G NR Signal Example:

3275 Data carriers

Spaced by 30 kHz

Total bandwidth ~ 98.25 MHz

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